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Thinking Big: Science and technology needs for large-scale geological carbon storage experiments

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Abstract

Geological carbon sequestration has emerged as a key potential technology pathway for reducing greenhouse gas emissions and stabilizing concentrations. Such a pathway requires 1000's of large volume injection facilities distributed globally with very low percentages of leakage. Although several large-scale projects exist, they do not currently cover a wide enough range of geological conditions to demonstrate that this technology pathway is likely to succeed. Similarly, current measurement, monitoring, and verification technology may not accurate document either injection volumes or leakage risk and activity within the full necessary range of important geological conditions.

To resolve these concerns, many large-volume, high-rate injection projects must proceed rapidly in order to serve two critical goals. The first is to demonstrate successful injection over a range of conditions, thereby testing "plays" for carbon storage. The second is to develop key science and technology experimentally to expedite the deployment of storage and improve the confidence of leakage monitoring and overall safety. In order for these goals to be met, injection must occur at a large scale due to the intrinsic difficulties of subsurface characterization, the scale of key geological heterogeneities, and the amount of signal necessary for successful monitoring and risk assessment. These facts also highlight the need for detailed and comprehensive geological assessment at any large-volume injection site before injection begins in order to understand local capacity, specific injectivity, potential leakage fast paths, and reservoir heterogeneity and integrity.

Introduction

Concerns over global climate change from anthropogenic emissions has prompted investigation into low-carbon or no-carbon energy sources [e.g., 1]. Such sources include nuclear fission, wind power, solar PV, and fuel biomass. Among decarbonized energy options, carbon sequestration has emerged as a critical element of any economic or policy investigation. From a range of carbon sequestration options, geological storage has gained importance as a relatively cheap, benign, and actionable approach, and one which can continue to utilize most aspects of the current global energy infrastructure [2,3]. Although much work has focused on the economic and engineering hurdles to widespread deployment of carbon storage technologies, much remains to be understood about the "tail end" of the system, namely the geological reservoirs anticipated to hold the carbon for long time scales.

Within this context, the enormous scale of the enterprise presents and important focus. As an example, Caldeira et al. [4] argue that, within the range of climate sensitivities modeled, roughly one 400 MW to 1400 MW zero-emissions power plant would need to be built every day for the next 50 years to achieve stabilization within a given risk framework. For comparison, a typical 1000 MW pulverized coal plant produces 6-8 Mt/y of CO2; a 500 MW IGCC would produce roughly 3 Mt/y [5,6]. Such enormous volumes of CO_2 would require a massive deployment of capture and storage infrastructure, as well as suitable geological reservoirs to serve as injection targets. This latter point is the focus of this paper.

Specifically, it is not clear that such an enterprise can succeed given the uncertainties in subsurface geological systems. In order to demonstrate success for such a large effort, one must demonstrate that many different geological conditions and configurations are likely to hold large CO_2 volumes for many hundreds of years. In addition, these reservoirs would have to present local populations and decision makers with a low-risk regarding public safety of the environment. These questions and concerns are best met through a combination of large-scale injection projects within the next few years. Such projects must involve large volumes of CO_2 (e.g., >100,000 tons/yr) injected over a long period of time (e.g., >5 years) in order to properly understand and address key scientific questions and concerns. Many relatively low cost, high volume opportunities exist [7,8] that could serve these ends.

Demo Projects and Field Experiments

There are important distinctions between the goals of demo projects and field experiments with regard to carbon storage. The goal of a demo project in this context is commonly to store large volumes of CO_2 for many years economically [e.g., 9]. The aim is a demonstration of viability, e.g., minimal leakage or capture. Demo projects often have economic or political drivers, and as such are likely to be more common. Towards this end, for example, the stated main function of the carbon storage partnerships sponsored by the DOE is the assessment of potential demo projects within a region based on aspects or regional geology, terrain, climate, or industry [e.g,. 10]. However, such a project may proceed with minimal development of new technology or information, and is naturally risk and cost averse. As such, monitoring technology may not be widely deployed, or a limited suite may be chosen.

In contrast, the chief goal of a field experiment is new knowledge, with regard to either specific science or technology development. The Frio project [11,12] is one example. Ideally, such knowledge should be widely applicable, even global in implications, to maximize the return on scientific investment. The aims of field experiments are focused on a specific set of learnings, e.g., viability of MMV technology or chemical evolution of rock-brine-gas systems. Since there may not be short-term economic or political drivers surrounding a field experiment, they are naturally scarcer.

Obviously, there is intersection between these domains. Weyburn is an example of a demonstration project driven largely by economic concerns, but also a site for deployment of experiments and tools [e.g., 13,14]. The experimental aspects "piggy-backed" onto the existing project, providing a platform for research that was much cheaper than an experimental execution of the same project. Ultimately, however, there will be many instances where this is either not possible or not desired. In this context, the Mountaineer project [15] might prove to be an excellent proposed demonstration project, but may not succeed as a field experimental facility due to a variety of factors, including local geology and geophysics.

In order to gain the practical and fundamental knowledge needed to deploy CO_2 storage at a very large scale (> 1 Gt C/yr), both demonstration projects and field experiments are needed. Of crucial importance, both efforts must proceed at a large scale, due to the inherent aspects of subsurface work. These include the spatial distribution and scale of key heterogeneities, such as internal reservoir baffles & barriers or faults with high leakage risk. In addition, the need for unambiguous geophysical or geochemical signals in monitoring often requires large volumes of injected CO_2 for detection. Finally, all subsurface characterization is prone to initial surprises and reworking. These conclusions are borne out of the two large-scale projects in operation today.

Sleipner and Weyburn as Learning Opportunities

The two large-scale projects, Sleipner and Weyburn, are widely cited as successes in carbon storage [e.g., 13,16]. They have proven to a first order that large volumes of CO_2 may be injected and stored with relatively low cost and no significant environmental or health damages. In addition, both projects that the CO_2 plume can be imaged, tracked, and modeled, increasing the confidence of operators that geological storage is viable from an MMV standpoint. While few would debate these points, both projects revealed the limits of proper geological characterization, and as such non-negligible surprises surfaced within each effort.

Sleipner has received over 6 MM tons of CO_2 over the past seven years with no demonstrable, and as such is an outstanding example of successful carbon storage. However, predictions of the CO_2 bubble evolution did not match the actual injection trajectory. Thin shale layers within the reservoir baffled the bubble, producing a more vertically distributed, aerially concentrated bubble [e.g., 17]. While this probably increases the total mineral storage and solubility [18], it is noteworthy as a failure of prediction. Similarly, the bubble was expected to flow towards the east. It ultimately flowed more northward than predicted, in part due to problems in the seismic modeling of the reservoir top and an unmapped north-trending geological feature that diverted flow [16]. These results are not altogether surprising given the relative lack of penetrations through and study of the Utsira Formation and lack of previous production or injection history.

Weyburn does not lack data [19]. The field was produced for over 50 years before CO_2 injection and had already received a water flood. The field has thousands of wells and many cores for proper reservoir characterization. Detailed geological and geophysical reservoir models using these data provided a predictive framework for subsurface fluid flow [e.g., 14]. However, that did not prevent significant surprises from arising. To begin, seismic imaging of the reservoir proved to be more complicated than expected, and the repeat seismic surveys required significant filtering and gaining to image the impedance contrasts associated with CO_2 injection [20]. In addition, certain zones showed surprisingly low injectivity, reducing the volume of injection and the attendant signal recognition. Finally, although previous workers had recognized the importance of fracture within the reservoir, only one geometric set of fracture was expected to dominate flow paths. A second set, however, showed surprising injectivity and diverted CO_2 volumes into unexpected portions of the reservoir [20,21]. Again, while this ultimately did not significantly affect EOR volumes or result in leakage, it demonstrated the difficulty in predicting subsurface conditions to a high level of accuracy.

Although none of these problems greatly increased the risk of either venture, they are noteworthy in two regards. First, neither was predicted, but both occurred, each affecting the physical distribution of CO_2 in space in time. Second, if smaller volumes of CO_2 were used, the projects would not have been seen. This is because heterogeneity in geological reservoirs is non-linear in their distribution. Because such features affect energy and mineral resources, there is a considerable literature addressing the issues of heterogeneities in "geobodies", and this remains an area of active research in sedimentology and stratigraphy.

Finally, while both of these projects are world-class examples of geological carbon storage, they are not necessarily representative of future storage options. In the case of Sleipner, the main target reservoir, the Utsira formation, is not really representative of most saline aquifer targets where injection currently operates [22]. Its large thickness (>300 ft), high porosity (>30%), high permeability (>3000 mD), high sand percent (>90) are unusual and are not representative of most saline aquifers in the US, Europe or sedimentary basins worldwide [e.g., 23]. Similarly, the shallow depth of injection (~2500 ft), which improves the quality of seismic imaging considerably, is equally atypical. Weyburn, in contrast, is typical of many target reservoirs in terms of target depths, permeability, porosity, and imaging potential. However, the field is blessed with an anhydrite cap-rock [14,19], uncommonly strong, dense, and impermeable. Within the general pool of depleted oil fields, small in total volume compared to saline aquifer, few have such exceptional cap-rocks [e.g., 24]. Moreover, the extremely high density and quality of data may not be typical of many current and future depleted field targets, and is absolutely not typical of saline aquifer targets.

The Key Range of Geological Conditions

Ultimately, each of these projects is a success in its own right, but only tests one "play" within the system. By analogy with hydrocarbon exploration, a play involves one reservoir type and one trapping configuration (in the case of CO_2 storage, either static or dynamic, c.f. [25]). Within a given basin, there are likely to be many plays, some riskier, costlier, or more viable than others. In order to maximize the potential for geological storage in the US and globally, multiple plays should be characterized through multiple dedicated demonstration projects and field experiments.

In order to understand the true viability of a large-scale deployment of CO_2 injection facilities across many different plays, one must try to delineate and characterize the pertinent range of injection conditions at depth. Injection is likely to proceed at depths >800 m in order to achieve supercritical or fluid CO_2 phases and <5000 m in order to reduce drilling costs. In order to achieve high rates of injection, permeability is likely to be >10 mD and porosity >10%. Within these conditions, however, there remains an enormous range of geological circumstances. Table 1 attempts to present the most important variable and their associated uncertainties.

Geological target type	Critical uncertainty	Geological Variable 1	Geological Variable 2	Geological Variable 3
Depleted Oil & Gas fields	Cap-rock integrity	Rock type (composition, permeability, strength)	Rock strength (thickness, burial history)	Effect of well perforations
	Total hydrocarbon solubility and miscibility	Reservoir temperature & pressure	Hydrocarbon composition (e.g., API gravity)	Brine composition
Saline Aquifers	Injectivity at depth	Depth and thickness	High vs. low permeability & porosity	Reservoir complexity (sand percent, fractures)
	Total solubility	Brine salinity and pH	Reservoir pressure and temperature	Rock composition (clastic vs. carbonate, mineral storage potential)
	Risk of fast-path leakage	Density and offset of local faults	Trapping configuration (static vs. dynamic)	Cap rock integrity
Unmineable coals	Porosity and permeability distribution	Cleat structure at depth	Matrix porosity vs maximum burial depth	Variations with rank and composition
	Total adsorption	Rank and composition	Effects of other gases	Leakage risks

Attempting to capture each case with a high and low case for each variable would result in roughly fifty independent experiments to understand each variable. Such an approach is fundamentally untenable. Thankfully, many of these geological variables are duplicated between fields and basins, and many of these circumstances are geologically coincident. For example, one field or target area may host both shallow and deep reservoirs, several types of coals, and multiple reservoir and brine compositions. As such, the number of independent circumstances can probably be collapsed into 10 or 12 sites that could maximize scientific and technical development. These sites could be selected based on their ability to extrapolate learnings to other basins and targets as well as issues such as regulatory environment and cost.

Within the context of scientific and technical excellence, a number of specific tasks will need to be the focus of the initial sets of large-scale projects. The tasks are necessary to address key concerns outside of the geoscience, such as environmental and public health risks.

Capacity estimation: Significant uncertainty remains in all potential geological reservoir classes regarding reservoir capacity [26,27,28]. In saline aquifers, uncertainties include composition or rocks and brines, solubility, geometric effects, and irreducible water saturation [e.g., 29,30]. In depleted hydrocarbon reservoirs, uncertainty includes all the uncertainties for saline aquifers plus uncertainties in miscibility and maximum hydrocarbon saturation [e.g. 31-33]. In unmineable coals, there remain uncertainties involving effective exchange, the effects of rank, mineralogy and composition, and cleat storage potential [e.g., 34,35]. In any given large-scale injection project, then, estimates should be put forward regarding minimum and maximum storage capacity. These predictions should be tested through monitoring, measurement, and verification (MMV) as well as syn- and post-injection drilling.

Leakage Risks: Risks to human populations and environmental systems remain a significant potential concern of large-scale deployment of carbon storage [e.g., 36]. Many uncertainties exist regarding the likelihood of seal failure [e.g., 37], including the probability at a given site, the rate of leakage, the magnitude of leakage, and the potential adverse affects. Large-scale projects should work vigorously to make quantitative predictions about the probability, rate, and location of potential leaks before injection, and use MMV technologies to demonstrate the accuracy and precision of such predictions.

Cost management: Recent efforts to understand geological carbon suggest that the uncertainties in storage costs are large and require improvement [e.g., 5]. Part of the reason behind this uncertainty lies in several issues:

- The wide range of geological settings for carbon storage
- The uncertainties in risk and associated costs (e.g., litigation)
- The number of wells needed for injection, and
- The costs of MMV introduction and maintenance

Large-scale projects should each proceed in a fashion to maximize the scientific and technology learnings as well as to develop a regional understanding of potential plays. However, a national and international strategy is required to make sure that sufficient diversity exists between projects to address issues of cost overall. The portfolio of projects globally should ultimately enable workers to provide high, low, and median cost estimates for a given project.

Monitoring, Measurement, and Verification (MMV): The current understanding of geological storage options comes in large part from the successes of MMV technologies in locations like Weyburn and Sleipner. Most of the current emphasis has been on 3D and 4D reflection seismology, chiefly to constrain the distribution of the CO_2 plume. Relatively little effort has focused on using attributes of the seismic volumes and the multi-component arrays in order to quantify the nature, concentration, and phase state of subsurface CO_2. Perhaps more importantly, these data are expensive to collect, are locally invasive, require months between iterations, and require highly specialized workers to plan, execute, and interpret these data. A current shortage of such workers might ultimately produce a bottleneck in the deployment of CO_2 storage.

Large-scale projects should use a wide array of monitoring approaches as appropriate, including both geophysical and geochemical techniques. Examples of such technologies include tilt-meters, passive source microseismic mapping, electrical resistance tomography (ERT), chemical tracers, soil chemistry studies, and deployment of atmospheric eddy correlation towers. Use of multiple approaches will help to demonstrate that monitoring and verification is possible over a wide range of geological and geographical circumstances. That information will help to allay concerns over the efficacy and safety of storage. It will also help to produce a set of practices regarding what technologies are best suited to a specific reservoir and setting. Finally, it will ultimately help reduce and manage costs by analyzing a suite of technologies that might be used quickly and cheaply in many settings. Ultimately, such information will also help regulators develop a strategy for monitoring subsurface injection efforts.

Discussion

While significant uncertainties exist regarding geological storage, these uncertainties can be managed, qualified, and ultimately quantified through a program of dedicated, large scale projects aimed at testing a variety of plays and understanding the basic science involved in storage. These uncertainties can play an important role in shaping economic models, policy rubrics, regulatory frameworks, and market mechanisms for carbon trading. Large-volume experiments and demonstrations will be needed to address crucial concerns in these areas.

Uncertainties in cost are still large. Although there are some estimates of the economics around storage [5], they do not directly address the uncertainties in drilling costs. Many oil fields have required infill drilling to very high densities (as much a 5 acre spacing) in order to properly access the subsurface fluid volumes given the heterogeneity and properties of the reservoir. Often, these wells are not recognized as necessary until more than 5 years into production. Long-reach horizontal wells and deep wells can increase both the injectivity and total storage of CO_2 in a reservoir [32], but commonly are more expensive than conventional wells. Large-scale projects will help to circumscribe the range of likely situations thus providing templates for cost estimations

Managing risk of leakage and contamination is widely believed to be highly important in gaining acceptance of geological carbon storage from the public [35]. Such acceptance is likely to depend in large part on convincing technical and scientific arguments demonstrating a broad understanding of such risks, and potentially the ability to warn populations or mitigate negative effects. Well-developed and tested MMV technology and a sound understand of subsurface geology and geochemistry will greatly improve the case for safe storage, all of which would be accelerated and strengthened through many large-scale experiments over a range of geological and geophysical conditions.

Similarly, it is widely recognized that proper evolution of carbon management institutions will require scientific and technical investment and understanding. Cap and trade schemes, GHG market development, and regulatory frameworks will both require MMV technology at their core that is well calibrated, reproducible, and able to be deployed widely. Economic analysts and markets will probably require solid demonstration of this capability by more than one entity or agency. Large-scale projects would serve a critical role in solidifying the market bases and provide an early platform to develop market and regulatory institutions as well.

The Teapot Dome Field Experiment

To help address the geoscience concerns discussed in this paper, the U.S. Department of Energy has designated the Teapot Dome oil field as a carbon sequestration field experimental facility. The field is owned by the US Government and operated by DOE as the Naval Petroleum Reserve #3 and the Rocky Mountain Oilfield Testing Center (RMOTC). The Teapot Dome center's primary purpose will be to serve as a platform for field experiments aimed at providing new science and technology for geological carbon storage in general. The field contains over 1600 wells, with a range of logging tools and cores, which serve as the primary data set. The field also has over 100 years of production data, including the results from steam and water floods and a recently acquired 3D seismic survey. As such, Teapot Dome provides a high-resolution, stable platform for long-term experiments (7-10 years) as well as high-risk experiments and novel approaches.

The field itself contains nine stratigraphic units that bear oil, and at least six that bear water. The depth of potential injection targets ranges from 500 to 8000 ft, and as such could contain CO_2 as a gas or supercritical fluid. Thermal gradient is roughly 1ºC/100 ft., although some deeper units show elevated water temperatures. Target permeability ranges from >300 mD to <1 mD, providing nearly 3 orders of magnitude permeability change. The field includes both siliciclastic and carbonate reservoirs, and a wide range of depositional systems including eolian, fluvial, tidal, deltaic, and shoreface units, some with significant fracture permeability. As such, the field provides an astonishing geological, geophysical, and geochemical range – by far the largest of any experimental facility. It also can examine questions of hydrocarbon miscibility, which can affect both total storage and ultimate recovery. Importantly, the field has a high local potential for leakage as well as storage. As such, experiments can proceed targeted at leakage monitoring, management, and even mitigation.

The potential impact of this facility on national and international carbon sequestration efforts is likely to be large. Due to the specific geology of the field, results from Teapot Dome could be immediately applied to other carbon storage and EOR efforts within the Rocky Mountains region. Similarly, many of the results could be applied to geological carbon storage efforts in California, the Gulf Coast region, the Illinois Basin, and other US and international basins. For these very reasons, the Teapot Dome facilities would also serve as an excellent training center for government, academic, and industrial investigators. Hopefully, other large-scale projects can use Teapot Dome as a model for operation and suitability regarding the most important scientific concerns facing the community.

Conclusions

1. Large-volume CO_2 injection projects are critical to the development of key science and technology learnings necessary for safe, successful deployment of geological carbon storage worldwide. Small-volume project are unlikely to accurately capture the subsurface heterogeneities that will affect long term injectivity and leakage risk.

2. Both demonstration projects and field experimental projects are needed to produce the rapid expansion of knowledge needed to test geological carbon

storage as a useful mitigation strategy to GHG emissions. It should be recognized the goals of both types of projects are ultimately different and should be managed differently.

3. In order to truly address the current uncertainties in geological carbon storage, many test sites are needed in order to capture the range of geologically important targets. Such sites should focus on MMV technology

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